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# A new simplified method for the measurement of water-leaving radiance

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**Abstract:** A new simplified method to measure water-leaving radiance was developed by combined use of a miniature spectrophotometer, a collimator, and a narrow pipe to block reflected sunlight from the sea surface. The instrument was handy, light-weighted and least expensive compared with those available for commercial use. The water-leaving radiance was determined by using the above-mentioned setup in the East China Sea, the Seto Inland Sea, and Shonai-ko of Lake Hamana. These areas covered a wide range of water mass types from clear to turbid water, and the new method was successfully implemented in all the areas. Signal to noise ratios of remote sensing reflectance $R_{rs}$ measured by the instrument were satisfactorily small by taking running mean of 7 data readings over about 1.3 nm and by sampling of 1 nm interval. However, noises were not negligible in a low $R_{rs}$ range below 0.001 sr$^{-1}$ which occurred in the longer wavelength range than 650 nm. The estimated errors due to self-shading were satisfactorily small (< 5%) in the wavelength range from 400 to 590 nm.

***Keywords:*** *water-leaving radiance, ocean-color remote sensing, spectrophotometer, USB4000*

## 1. Introduction

Water-leaving radiance, which is the upwelling radiance emitted from the sea to the air, is one of the most important parameters for ocean-color remote sensing. Water-leaving radiance is determined from the total radiance measured by satellite ocean-color sensors with the implementation of atmospheric correction (GORDON and CLARK, 1980; FUKUSHIMA *et al.*, 1998). However, the obtained water-leaving radiance is dependent on both solar altitude and the conditions of the air parameters used for the correction. Therefore, it is essential to validate the atmospheric corrections and in-water algorithms in order to determine the water-leaving radiance in situ. In ocean-color remote sensing, remote sensing reflectance, which is the water-leaving radiance divided by the incident solar irradiance just above the sea surface, is used to retrieve properties of seawater, including chlorophyll *a* concentration, suspended mater, and dissolved organic matter (GORDON and MOREL, 1983; KISHINO *et al.*, 1998; O'REILLY *et al.*, 1998). Thus, water-leaving radiance is a key parameter in ocean-color remote sensing and is used not only for validations, but also for the development of new in-water algorithms. Water-

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leaving radiance also allows for the vicarious calibration of the satellite ocean-color sensors (McCLAIN *et al.*, 2000).

Water-leaving radiance is usually measured by a spectrophotometer mounted on a tower top or on the upper deck of a research vessel. The present communication describes a new simplified method for the in situ measurement of the water-leaving radiance by using convenient and less expensive instrumentation when compared with commercially available instruments.

## 2. Issues associated with conventional methods

Water-leaving radiance is measured from the upwelling radiance at, or near, the sea surface by the use of an in-water spectrophotometer (e.g., PRR-800, SuBOPS) (KISHINO *et al.*, 1997; MORROW *et al.*, 2010), from the calculations on a handheld instrument (e.g., SIMBAD), or from a photometer system (e.g., RAMSES, SeaPRISM) mounted on the upper deck or tower top of a research vessel (HOKKER *et al.*, 2000; ISHIZAKA *et al.* personal communications). The direct measurement of water-leaving radiance needs to avoid the sea surface reflectance (TANAKA *et al.*, 2006; LEE *et al.*, 2013).

An underwater spectrophotometer used for the estimation of water-leaving radiance consists of an onboard spectral irradiance meter, an underwater unit fitted with a downwelling irradiance meter and an upwelling radiance meter, and an interface unit that has a battery power source. The attenuation coefficient of the upwelling radiance, $K_u$, is calculated from an upwelling radiance profile near the sea surface, $L_u$ (z, $\lambda$):

$$K_u(\lambda)=\frac{1}{(z_1-z_0)}\ln\frac{L_u(z_0,\lambda)}{L_u(z_1,\lambda)}.$$

Then, the upwelling radiance just below the sea surface, $L_u$ ($0^-$, $\lambda$), is extrapolated:

$$L_u(0^-,\lambda)=L_u(z_0,\lambda)\exp[z_0,\lambda]\exp[z_0,K_u(\lambda)].$$

The water-leaving radiance, $L_w$ ($\lambda$), is calculated from $L_u$ ($0^-$, $\lambda$), which, according to AUSTIN (1974), is:

$$L_w(\lambda)=\frac{1-\rho(\lambda)}{n(\lambda)^2}L_u(0^-,\lambda).$$

where $\rho(\lambda)$ is the Fresnel surface reflectance and $n$ ($\lambda$) is the refractive index of seawater. The remote sensing reflectance, $R_{rs}$ ($\lambda$), is obtained from $L_w(\lambda)$ and the spectral irradiance of the incident sea surface, $E_{ds}$ ($\lambda$):

$$R_{rs}(\lambda)=\frac{L_w(\lambda)}{E_{ds}(\lambda)}=\frac{1-\rho(\lambda)}{n(\lambda)^2}\frac{L_u(0^-,\lambda)}{E_{ds}(\lambda)}..$$

The normalized water-leaving radiance, $L_{nw}$ ($\lambda$), can be obtained from the remote sensing reflectance and extraterrestrial solar irradiance, $F_o$ ($\lambda$):

$$L_{nw}(\lambda)=F_o(\lambda)\times R_{rs}(\lambda).$$

Errors in the estimation of water-leaving radiance are considered to originate from the self-shading caused by the size of the photometer (AAS, 1969; TANAKA *et al.*, 2006) and the variations in measured radiance and the depth caused by sea surface wave motion. However, the data measured by an underwater photometer are used not only to estimate water-leaving radiance, but also to determine the spectral distribution of underwater light in optical studies of light field and phytoplankton photosynthesis.

In general practice, a photometer system mounted on the upper deck or a tower top of a research vessel is composed of an irradiance meter and two radiance meters (Fig. 1). The irradiance meter measures the incident irradiance at the sea surface. The radiance meter is directed at the sea surface with a tangential angle

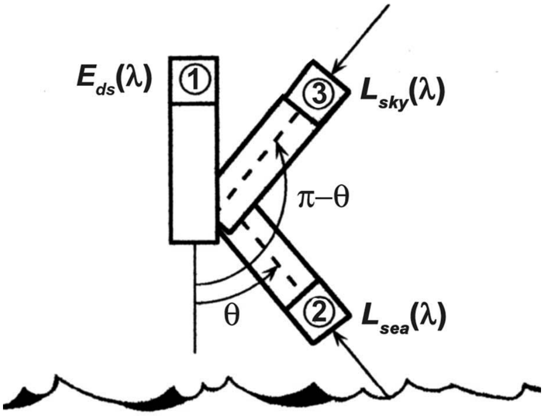


**Fig. 1** A schematic of the instruments on the top of the tower. For details, see text.
1 : Irradiance meter for incident irradiance at the sea surface
2 : Sea-viewing radiance meter for total radiance (above the surface)
3 : Sky-viewing radiance meter for indirect radiance

($\theta$) of 30° to 45° from the vertical axis and measures the total radiance, including the water-leaving radiance and the refracted sky radiance from the sea surface. The other radiance meter is directed towards the sky with an angle of 30° to 45° from the zenith axis ($\pi-\theta$) and measures the sky radiance.

The two radiances and the irradiance are calculated by using remote sensing reflectance (HOOKER *et al.*, 2003):

$$R_{rs}(\lambda)=[L_{sea}(\lambda)-rL_{sky}(\lambda)]/E_{ds}(\lambda),.,$$

where $L_{sea}$ ($\lambda$) is the total radiance (including water-leaving radiance and refracted sky radiance on the sea surface), $r$ is the sea surface reflectance, $L_{sky}$ ($\lambda$) is the sky radiance, and $E_{ds}$ ($\lambda$) is the incident irradiance of the sea surface.

Ishizaka and his group attempted to use a photometer system mounted on the upper deck of the express liners between Fukuoka and Pusan (ISHIZAKA, personal communication) to calculate the chlorophyll concentration along the cruise tracks. Their attempt resulted in limited success, mainly because the reflected sky radiance fluctuated in accordance with the roughness of the sea surface, the ship's shadow, and white bubbles. Thus, it is difficult to obtain a stable measurement of the radiance. If water-leaving radiance has a bi-directional function, the normalized water-leaving radiance can have large errors.

A method for the direct measurement of water-leaving radiance was proposed by TANAKA *et al.* (2006), who used the RAMSES-ARC (TriOS GmbH) as a radiance sensor. They measured the water-leaving radiance with an underwater spectral upwelling radiometer, PRR-800, in Katagami Bay, Nagasaki, on the west side of Kyusyu, Japan. However, a dome cover used by TANAKA *et al.* (2006) resulted in large errors due to self-shading because the dome was too large, measuring 15 cm in diameter (GORDON and DING, 1992).

## 3. Direct measurement of water-leaving radiance

For the direct measurement of the water-leaving radiance, we present a new simplified instrument that is composed of a miniature spectrophotometer (USB-4000, Ocean Optics) connected with a collimator placed at the top end of an opaque vinyl chloride pipe (Fig. 2). A major advantage of the USB-4000 is its portability with a reasonable price, and wavelength resolution. A total cost of the proposed system including a PC is less than one third of that of RAMSES (TriOS) of a similar sensing configuration to the proposed one. RAMSES is installed in a pressure-resistant container which enables its use down to 300 m depth. But, we do not need such consideration to hydro-pressure in our purpose to measure at the

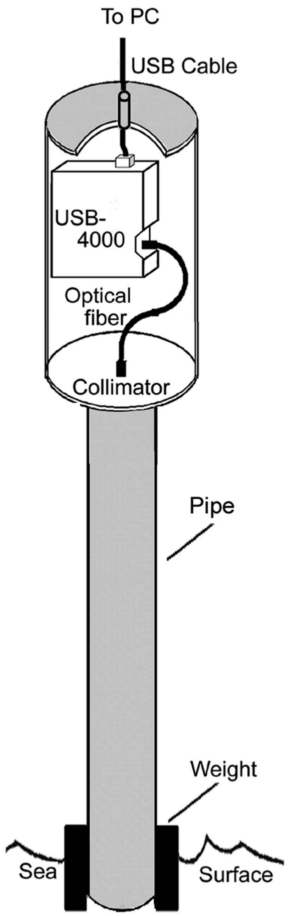


**Fig. 2** Configuration of a new simplified instrument

surface. Furthermore, the USB-4000 provides the output of a finer wavelength resolution than that of RAMSES, as exemplified by an observation that the former can detect sharp emission lines of fluorescence tubes, but the latter gives only their broad peaks.

The detector of the USB-4000 has a CCD array, which has 3648 elements. The wavelength range is between 400 nm and 750 nm. The overall wavelength resolution is approximately 1.33 nm with 25 $\mu$ m of the entrance aperture of spectrometer. The pipe is 5 cm in diameter and 50 cm long, whose inside is painted black to prevent reflection. The field of view of the radiance meter is limited to 5° 45′ by the diameter of the pipe. The signals from the spectrophotometer are sent to a PC via a USB cable. The other end of the pipe is fitted with a 2-kg weight to keep the pipe in a vertical position and soaked in seawater in order to measure the water-leaving radiance without interference from the reflected sky radiance. In the actual measurements, the instrument was hanged by a thin rope to keep the instrument stably at the vertical direction with the other end of a pipe dipped into the water within 10 cm.

In general practice, the incident irradiance ($E_{ds}$) of the sea surface is obtained from radiance measured by a standard white diffuser, and the radiance reflected from the standard diffuser tends to be higher than the water-leaving radiance. However, since the remote sensing reflectance is generally in the range of 0.002 $sr^{-1}$ or 0.003 $sr^{-1}$, occasionally exceeding 0.01 $sr^{-1}$ between 500 nm and 555 nm, the instrumental sensitivity has to be raised for measurement of the water-leaving radiance. Here, we propose the use of a gray reflectance plate as a substandard. This enables to maintain the same instrumental sensitivity for measurement of both incident and water-leaving radiance. This procedure facilitates measurements by easy comparison of both measurements, and by eliminating switching the instrumental sensitivity. The gray plate was made of a homogeneous mixture of plaster and black India ink. The reflectance of the plate followed the cosine law and approximately 10% of reflectance intensity compared with a commonly used white standard was most convenient. In the following measurements, we used a gray plate of 11% reflectance. The incident irradiance at the sea surface, $E_{ds}$ ($\lambda$), is obtained as follows:

$$E_{ds}(\lambda)=\pi L_G(\lambda)/G_r(\lambda).$$

Then, the remote sensing reflectance, $R_{rs}$ ($\lambda$), is

$$R_{rs}(\lambda)=\frac{L_w(\lambda)}{\pi L_G(\lambda)/G_r(\lambda)}=\frac{L_w(\lambda)}{E_{ds}(\lambda)},$$

where $L_G$ $(\lambda)$ and $G_r$ $(\lambda)$ are the radiance and reflectance of the gray plate, respectively.

While the proposed instrument does not have an optical shutter, the dark current can be monitored by covering with a cap at the end of measuring pipe. Next, after removing the cap, water-leaving radiance, $L_w(\lambda)$, is measured. Then the dark value is re-confirmed with the cap again. The influence of temperature dependence on dark current is eliminated in this way. In a similar manner, the incident irradiance at the sea surface, $E_{ds}$ $(\lambda)$, is measured using the gray diffuser. The time required is within 5 minute.

## 4. Measurement

The new method was verified by in situ tests in the East China Sea, the Seto Inland Sea, and Shonai-ko of Lake Hamana. The test in the East China Sea was conducted on September 5–13, 2007 during the RV Tansei Maru cruise (KT-07-22) within Kuroshio, where the water was very clear and blue in color. The Seto Inland Sea was surveyed on board the RV Nauplius on July 19 and August 24, 2007, when dense blooms of diatoms occurred off Harimanada with yellowish green color at the surface. Shonai-ko of Lake Hamana was visited on July 9 and 17, 2008, when mixed red tides of diatoms and dinoflagellates occurred, which caused the water to take on the color of soy sauce. $R_{rs}$ was obtained by running mean of 7 consecutive data readings over about 1.3 nm, and by sampling of 1 nm interval based on preliminary examinations to reduce influences of noise.

Concentrations of chlorophyll *a* were very low, ranging between 0.03 and 0.15 mg m$^{-3}$, in the East China Sea, and typical reflectance in blue water was observed. Remote sensing reflectance in the East China Sea was high at short wavelengths and decreased toward longer wavelengths to reach almost zero at a wavelength of 600 nm (Fig. 3).

The concentrations of chlorophyll *a* varied considerably, ranging from 0.35 to 14.24 mg m$^{-3}$, in the Seto Inland Sea. Remote sensing reflectance showed peaks at wavelengths around 580 nm and at 685 nm (Fig. 4). The latter maximum was the result of chlorophyll fluorescence (KISHINO *et al*., 1984).

The remote sensing reflectance at Shonai-ko of Lake Hamana was high, ranging between 500 and 650 nm, and exhibited a maximum at a wavelength of 700 nm (Fig. 5). These high values resulted from a combination of scattering and fluorescence and appeared to shift towards longer wavelengths (KISHINO *et al*., 1986). Small

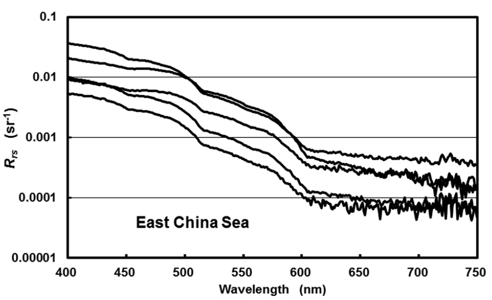


**Fig. 3** Remote sensing reflectance $R_{rs}$ in the East China Sea measured between 10:00 and 15:00 on September 5–13, 2007 during the RV Tansei Maru cruise (KT-07-22).

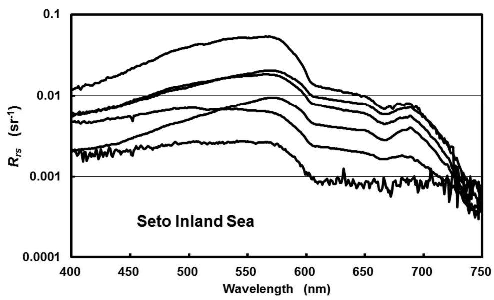


**Fig. 4** Remote sensing reflectance $R_{rs}$ in the Seto Inland Sea measured on July 19, 2007.

maximums were found at wavelengths of 560 to 600 nm and 645 nm. These maximums corresponded to the minimum of dinoflagellates absorption. The concentration of chlorophyll *a* ranged from 13.75 at the mouth of the lake to 77.98 mg m$^{-3}$ at its innermost part.

$R_{rs}$ measured by the new instrument and PRR-800 was compared by simultaneous measurements of both instruments at 6 stations during the KT07-22 cruise. $R_{rs}$ were calculated using USB-4000 fitted with band-pass filters with band width of ± 10 nm, and from $E_{ds}$ and $L_u$ obtained by using PRR-800. No significant variation in observation was noted among stations, and an example at a station was shown in Fig. 6. Both instrument yielded similar $R_{rs}$ values in the range of 380 -- 595 nm with a considerable discrepancy of USB 4000 from PRR-800 beyond 625 nm, probably due to electrical noise of USB-4000. Correlation coefficients at 6 stations varied between 0.949 and 0.999 with a mean of 0.987 ± 0.0018. between values obtained by both instruments. Thus, $R_{rs}$ obtained by both instruments can be regarded as identical below 595 nm.

Signal to noise ratio of the new instrument was examined. Signal-to-noise ratio of USB-4000 was 300: 1 at full signal according to instrumental specifications. The integration time was set at 100 msec at the high solar altitude. During a measurement conducted in clear ocean off Okinawa Islands in the East China Sea at 10:36 local time on 7 September, 2007, the solar radiance reflected by gray plate, $L_G$ was 5000 at the wavelength of 400 nm, increased to 42000 at 535 nm, and decreased to 15800 at 750 nm. This spectral distribution was almost identical to the spectral sensitivity of USB-4000. Noises fluctuated between 200 and 400 in the wavelength range from 400 to 750 nm. Then, signal to noise ratio was calculated to range between 12.5:1 and 107.5:1. The radiance from the sea surface, $L_w$ was 2550 at 400 nm, increasing to 5700 at 490 nm, decreasing to 400 at 600 nm, and 150 at 750 nm with noises ranging from 100 to 200 in the whole wavelength. Then, signal to noise ratio in the range from 400 to 600 nm varied from 2:1 to 28.5:1, and 0.75:1 to 2:1 in the range between 600 and 700 nm.

A similar analysis was made for turbid water at Shonai-ko of Lake Hamana at local time of 13:50 15 July, 2008, the solar radiance reflected by gray plate, $L_G$, was 3000 at the wavelength of 400 nm, was increasing to 32000 at 535 nm, and decreasing to 11000 at 750 nm. The noises were between 200 and 400 at wavelength from 400 to 750nm.

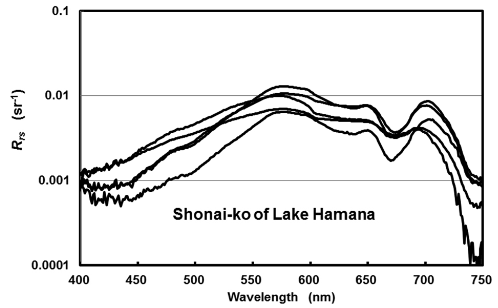


**Fig. 5** Remote sensing reflectance $R_{rs}$ at Shonai-ko of Lake Hamana measured on July 15, 2008.

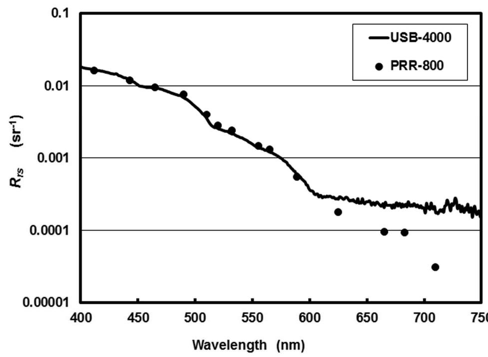


**Fig. 6** Comparison of remote sensing reflectance $R_{rs}$ measured by PRR-800 and USB-4000 in the East China Sea. Circles and a solid line denote values obtained by PRR-800 and USB-4000, respectively.

Then, signal to noise ratio ranged between 7.5:1 and 80:1. The radiance from the sea surface, $L_w$ was 200 at 400 nm, increased to 1200 at 500 nm, reached its maximum of 6500 at 580 nm, and decreased to 400 at 750 nm. Another secondary maximum of 2450 due to chlorophyll *a* fluorescence appeared at around 700 nm. The noises ranged between 100 and 200 at whole wavelength. Then, signal to noise ratio varied from 1:1 to 32.5:1 in the wavelength range from 400 to 600 nm, and from 2:1 to 15.1:1 between 600 and 750 nm except the wavelength range between 675 and 710 nm, where signal to noise ratio was large due to the chlorophyll *a* fluorescence.

These noise levels were reduced much to one third or fourth by taking a running mean of 7 data readings and by sampling at interval 1 nm. However, noises were not negligible even with this treatment in low $R_{rs}$ range below 0.001 $sr^{-1}$, which occurred in the longer wavelength range than 650 nm (Figs. 3, 4 and 5).

## 5. Discussion

The advantages of the new method are as follows: (1) it allows direct measurement of water-leaving radiance without the interference of reflected radiance at the sea surface; (2) it is handy for use on small boats; (3) there is no need for absolute calibration; and (4) it is inexpensive to make. A possible disadvantage is errors caused by the uncertainty of the depth of the bottom end of the pipe. The error becomes large with increasing depth of the bottom end and turbidity of seawater. The lack of need for absolute calibration means that the calibration errors would be less than 5% (MUELLER and AUSTIN, 1992). Other errors are caused by the ship's effects and self-shading. As is common in optical measurements, the new method is under the influence of the ship's shade (GORDON, 1985; SARUYA *et al*., 1997; Leathers *et al.*, 2004). According to the results of a Monte Carlo simulation and its field validation by SARUYA *et al.* (1997), the error in upward irradiance is much smaller than that for downward irradiance, but it is not negligibly small. Therefore, the use of a boom in order to avoid the shade is recommended.

Let us consider errors associated with self-shading. GORDON and DING (1992) estimated the diameter ($D_{max}$) of an optical instrument that produced an error of 5% of $R_s$ by the Monte-Carlo technique, and they showed an error associated with self-shading, $\varepsilon$ of an instrument whose diameter is $D$ as:

$$\varepsilon = 1- (0.95)\ D/D_{max},$$

Using this relationship and Figure 11 of GORDON and DING (1992), errors due to self-shading of the new instrument was estimated to be 1% or 2% between 350 nm and 590 nm, and lower than 5% from 600 nm to 650 nm when chlorophyll *a* concentration was 1 mg $m^{-3}$. In the longer wavelength range, the error increased to about 9% at 700 nm and sharply to about 30% at 740 nm. With high chlorophyll *a* concentration of 10 mg $m^{-3}$, the error increased to 2% or 3% between 350 nm and 580 nm, and below 5% between 590 and 640 nm. In the case of the PRR-800, the diameter of the photometer is 10.2 cm, and the error for water with chlorophyll *a* concentration of 1 mg $m^{-3}$ would be below 5% between 350 nm and 570 nm. In case of 10 mg $m^{-3}$ chlorophyll *a*, the errors would be lower than 5% at around 540 nm and below 7% at wavelength shorter than 590 nm. At longer wavelength the error increased sharply, for example, 17% at 700 nm, and over 50% at 740 nm. Based on these consideration, errors due to self-shading of the new instrument is half as that of PRR-800.

Let us consider a case where the water-leaving radiance is estimated by the upward spectral radiance measured at 1 m depth by using an underwater spectral irradiance meter. If the depth has an error of ± 0.1 m, then the error would be under 1% when $k_u$ is 0.05 $m^{-1}$ for very clear ocean water, ± 5% when $k_u$ is 0.5 $m^{-1}$, and about ± 10% when $k_u$ is 1 $m^{-1}$ in turbid coastal areas. It is believed that the water-leaving radiance can be estimated from 2 m depth. The error would be ± 1%, ± 10%, and ± 20% for $k_u$ values of 0.05 $m^{-1}$, 0.5 $m^{-1}$, and 1 $m^{-1}$, respectively. The error would become larger for larger values of $k_u$ and greater measured depths. The spectral attenuation coefficient of upward radiance, $k_u(\lambda)$, changes with wavelength, especially at large wavelengths. Thus, the error varies considerably with both depth and wavelength.

The reflected sky radiance by the sea surface is added to the water-leaving radiance in the case of tower or shipboard measurements. Water-leaving radiance can be obtained by the revision of the total sea radiance using the reflectance of the sea surface. The reflectance of the sea surface depends on the incident angle and surface conditions. The reflectance of a mirror-like sea surface follows Fresnel's law. The reflectance under an incident angle of 40° is about 2%, whereas reflectance values at incident angles greater than 40° can be up to 100% at 90°. In contrast, while the reflectance from wavy sea surface is a little larger than that of a flat surface at small incident angles, the reflectance at large incident angles is smaller than that of a flat surface (BURT, 1954; COX and MUNK, 1956; HISHIDA and KISHINO, 1965). Thus, the reflected radiance varies considerably in response to wave action. However, the reflectance is often regarded as a constant in the measurement of the water-leaving radiance in the case of the tower or shipboard is often used as a constant. For example, HOKKER *et al.* (2003) used 2.8% for the reflectance of the sky radiance at tower measurements. In addition, other factors than sea conditions must also be considered in the measurement of reflectance. The new simplified instrumentation is expected to facilitate in situ measurement of water-leaving radiance.

In conclusion, the new proposed pipe method for the direct measurement of water-leaving radiance is convenient and applicable in the field from the clear open ocean to turbid coastal or lake water environments. Moreover, the errors obtained are smaller than those obtained with previous methods.

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